UNIVERSITY OF DUNDEE

DRY FLY ASH

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INTRODUCTION AND USES IN CONCRETE

Fly ash (FA) is a by-product of the burning of coal at thermal power stations. It has been used as a cement component in concrete mixes normally at the 30 % level providing several technical benefits. Its requirements given in Table 1 have been defined in BS EN 450 and BS 3892.

Table 1 Requirements for fly ash given in BS EN 450 (1995) and BS 3892, Part 1 (1997)

Property	BS EN 450	BS 3892, Part 1
Fineness, max. (% retained on 45µm)	40.0	12.0
Fineness variation	± 10.0 on mean value.	--
Loss on Ignition, (%)	5.0 (7.0 on national basis) auto-controlled	7.0 max
Particle density (kg/m^3)	± 150 on mean value.	≥ 2000
Chemical Composition:		
SO_3, max. (%)	3.0	2.0
CaO - Free, max. (%)	1.0 or 2.5^(i)	--
CaO - Total, max. (%)	10 (sub-bituminous ashes)	10
Chloride, max. (%)	0.10	0.10
Moisture content, max. (%)	(ii)	0.5
Water requirement, max. (%)	--	95
Activity index, min. (%) (iii)	75 (28 days) 85 (90 days)	80 (28 days)
Soundness (mm)	10^(i)	10

(i) Soundness test required only if free CaO exceeds 1%.
(ii) Fly ash to be stored and transported dry
(iii) BS EN 450 uses 25% FA content by mass, test carried out on equal water content basis, whereas BS3892 uses 30% fly ash content by mass, test carried out on equal flow basis.

MANUFACTURE AND PROCESSING

Dry form is currently the most commonly used method of supplying fly ash. Dry fly ash is handled in a similar manner to Portland cement. Storage is in sealed silos with the associated filtration and desiccation equipment, or in bags.

Effect of ±10% fineness variation on strength

BS EN 450 allows fly ash with a fineness variation of ±10% of the suppliers declared mean value. Fly ash with this requirement, therefore, conform to the standard, but have a maximum difference of 20% in fineness, which may translate into a strength difference of between 1.6 and 6.0 N/mm^2 over a range of PC+FA contents from 250 to 550 kg/m^3 (Table 2).

Table 2 Effect of a 5% fineness variation on 28 day concrete cube strength (Dhir et al., 1996)

PC+FA content (kg/m^3)	Rate of strength change per 5% FA fineness variation (N/mm^2)	Strength range for ±10% BS EN 450 allowance (N/mm^2)
250	0.4	±0.8
350	0.6	±1.2
450	1.0	±2.0
550	1.5	±3.0

Loss-on-ignition

The upper limit on LOI of 7.0% is to be used in BS EN 450 on a national basis. This value is not known to cause any problems in the quality of fly ash and should provide no difficulties in engineering and durability properties. Unlike fineness, no limits on the maximum variability of LOI within the overall limit of 7.0% are specified. However, this has particular relevance to freeze-thaw resistance of concrete, and to the colour of concrete.

It is known that as the LOI of fly ash increases, the dosage of AEA required to achieve a specified air content increases. Therefore, using set mix proportions, any variation in the LOI of fly ash will lead to erratic air entrainment. Users of fly ash are therefore advised to pay particular attention to ensuring that fly ash of consistent LOI is used. Fly ash with high LOI are darker than those with low LOI, which is often reflected in the colour of the manufactured concrete. Where the appearance or colour of concrete is important, users should ensure that fly ash of consistent LOI is used to avoid fluctuations in gradation and shade.

PROPERTIES OF CONCRETE

Fresh Concrete Properties

Incorporation of fly ash in concrete, in general, reduces water demand, improves workability and reduces bleeding and segregation. The benefits associated with fly ash can enable water contents to be lower and hence concrete with reduced water/cement (w/c) ratio for equal workability can be designed (Dhir et al. 2002).

Strength Development

Research (Dhir et al., 1998) has shown that use of coarser fly ash leads to a reduction in compressive strength for equal w/c ratio. This effect increases with decreasing w/(PC+FA) ratio as shown in Figure 1. Generally, a 5% increase in 45 mm sieve retention will lead to a strength reduction of between 0.4 and 1.5 N/mm2 for typical PC+FA content.

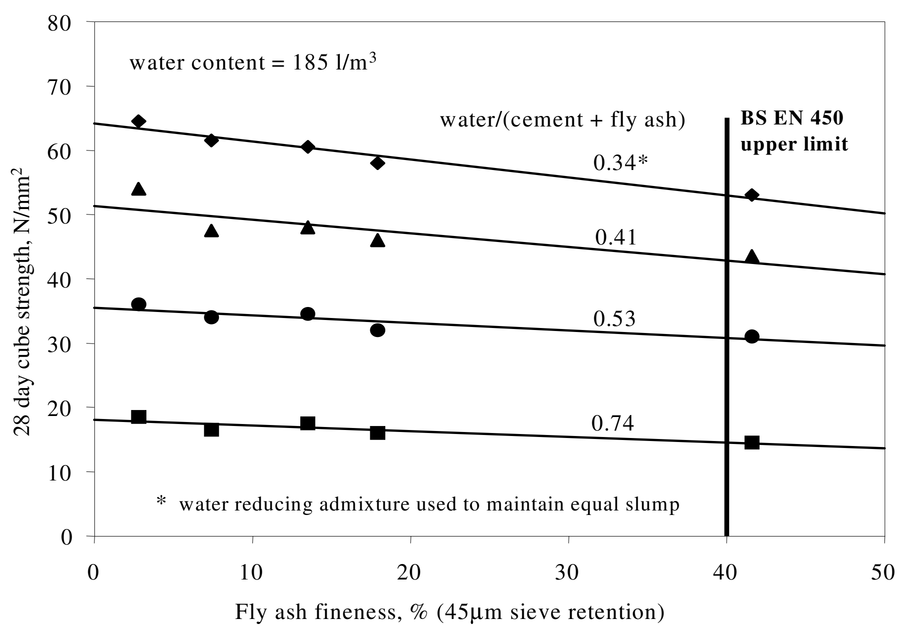

Figure 1 Relationship between FA fineness and 28 day strength (FA content = 30% by mass of PC+FA) (Dhir et al., 1998)

The pozzolanic reaction of fly ash in concrete is slower than PC at normal temperatures and it does not progress to any significant degree until several weeks giving slower strength development. Despite the low cement content, slow reaction process of fly ash, and use of superplasticiser, high volume fly ash concrete, in general, does not show unacceptable retardation in hardening, and demonstrates adequate strength at 1 day. However, special care and measures need to be taken in cold weather concreting, as combination of low cement content, superplasticizer, and low temperatures will result in considerable retardation of early strength (Bilodeau and Malhotra, 2000). Fly ash provides, when used in concrete, less temperature rise and this effect increases with the level of fly ash present (Atis, 2002).

It has been shown that concretes of equal strength can be produced using fly ash (fineness over the full range permitted in BS EN 450) as a concrete component. Strength may be controlled by adjusting the w/(PC+FA) ratio, changing the relative proportions of constituent materials or combinations of these.

ENGINEERING PROPERTIES

The influence of using different fineness of fly ash on the elastic modulus, creep coefficient and ultimate shrinkage of concrete are compared in Table 3. There are no significant effects of fly ash fineness, in general, on any of these properties when concretes have the same 28-day strength. However, the lower ultimate shrinkage for the coarser fly ash reflects the lower w/c ratio needed to achieve equal 28-day strength.

Durability

Influence of fly ash (fineness of 3.5% and 35.0%) on the durability characteristics of concrete are compared in Table 4 and details are given in the following sections.

Chloride ingress

Using fly ash in concrete improves the performance in chloride environments (Thomas, 1991). For equal strength fly ash concrete there is no significant effect of fineness or loss on ignition (LOI) on the resistance to chloride ingress (Dhir et al., 1996). Hence, all fly ash conforming to BS EN 450 are suitable for exposure in chloride environments.

Table 3 Comparison of engineering properties for concrete containing fly ashes of differing fineness (Dhir et al., 1986)

Engineering Property	Design Strength (N/mm^2)	Fly ash fineness 3.3%	Fly ash fineness 29.7%
(i) Elastic modulus	20	16	17
	40	23	23
	60	28	27
(ii) Creep coefficient	20	1.26	1.27
	40	1.11	1.13
	60	1.11	1.12
(iii) Ultimate Shrinkage (x 10^{-6})	20	393	320
	40	492	408
	60	660	602

FA content = 30% by mass of PC+FA
(i) elastic modulus tested at 28 days as BS 1881: Part 121, (ii) creep at 28 days loading (0.4 f_{cu}), (iii) ultimate shrinkage at 20°C, 55% RH

Table 4 Comparison of aspects of durability for concrete containing FA of differing fineness (Thomas, 1991)

Durability property	Design Strength (N/mm^2)	Fly ash fineness 3.5%	Fly ash fineness 35.0%
(i) chloride diffusion ($cm^2/s \times 10^{-9}$)	35	9.4	10.2
	50	4.9	4.3
	60	1.2	1.5
(ii) carbonation depth (mm)	25	31.0	32.0
	35	17.0	17.5
(iii) sulfate resistance, expansion ($\% \times 10^{-3}$)	25	41	45
	35	28	28
	50	0	0
(iv) Freeze-thaw durability factor (%)	35	51	48
	50	72	65
	35 †	98	97
(v) abrasion (mm) ‡	35	1.10	0.92
	50	0.79	0.80

FA content = 30% by mass of PC +FA
(i) two compartment cell, (ii) 4.0% enriched CO_2, 20°C, 55% RH (30 weeks), (iii) 6.0g/l $MgSO_4$ (184 days exposure), (iv) ASTM C666, Procedure A, (v) Modified BCA method.
† air entrained concrete, ‡ cured for seven days wrapped in polythene and then air at 20°C, 55% RH to 28 days

Carbonation

Research (Lewandowski, 1983; Schiessl and Hardtl, 1991; Dhir et al., 1996) has shown that the maximum difference in depth of carbonation between concrete specimens containing different qualities of fly ash has been found to be well within experimental variability. For practical purposes, it can be assumed, therefore, that fly ash fineness and LOI have no influence on carbonation rates. Hence, all fly ash conforming to BS EN 450 are suitable for exposure to environments in which carbonation may take place.

Sulfate resistance

Fly ash when used in concrete provides adequate resistance to the ettringite form of sulfate attack, which is generally regarded to reflect the reduction in quantity of reactive material present and the enhancement in the concrete microstructure (Dhir et al, 1991). Short-term tests have shown that fly ash concretes of similar strength have comparable resistance to sulfate attack, with concretes of strength greater than 50N/mm2 showing little expansion (Dhir et al., 1998). BS 8500, the complimentary UK standard to BS EN 206-1 recommends that a minimum of 25% fly ash by mass should be used where fly ash is used as cement component or in combination with a CEM I cement for sulfate resistance. No guidance can be given at present on the use of BS EN 450 FA to resist the thaumasite form of sulfate attack.

Freeze-thaw resistance

The rate of deterioration of concrete under freeze-thaw conditions decreases with an increase in concrete strength. For equal strength, no influence of fineness or LOI of fly ash on the performance of concrete specimens against freeze-thaw attack (Lewandowski, 1983; Dhir et al, 1998; Dhir et al., 1999). For satisfactory performance against freeze-thaw conditions, using air-entraining admixtures (AEA) in concrete enhances the resistance more than increasing the compressive strength alone. The dosage of AEA required to attain the necessary air content is approximately same for all fly ash fineness. However, for fly ash with high LOI, higher dosages of AEA may be needed for fly ash with low LOI. Particular attention should, therefore, be paid to any LOI and the subsequent air content and concrete strength to ensure that concrete freeze-thaw resistance is maintained.

- **Abrasion Resistance**

Research (Dhir et al, 1996) indicates that proper curing of concrete containing fine fly ash (3.5% and 13.5% retained on a 45mm sieve) provides a minor improvement in the abrasion resistance over that obtained using coarser fly ash (35% retained).

STANDARDS AND SPECIFICATIONS

Methods for Using BS EN 450 FA

Equivalent Cement Method

The equivalent cement method (any PC/FA combination that conforms to the equivalent cement standard will give adequate performance) in BS 3892: Part 1 is the most widely used method in the UK for controlling the incorporation of fly ash into concrete. It is used by the suppliers to demonstrate that a PC/FA combination from a defined source has the properties and proportions required by cement conforming to the equivalent cement standard. The procedure is applicable fly ash conforming to BS 3892: Part 1 and BS EN 450 with an LOI not greater than 7%. In fact, research (Dhir et al, 2000) has shown that the method is applicable to BS EN 450, an d its use is recommended. The procedure determines and uses the range of proportions over which the requirements of the cement standard are satisfied. This gives flexibility to optimise the mix design; however proportions of fly ash shall not exceed 55% of the combination. The applicable range, nevertheless, varies with the properties of the fly ash and cement.

K-value Method

The k-value approach (Smith, 1967) to using fly ash assumes that fly ash is “k” times as effective as an equal mass of cement in the development of strength, engineering properties and durability resistance. The “effective cement content” to be used in the calculation of minimum ‘cement’ content and maximum water/‘cement’ ratio is therefore calculated as $c + kf$, where c is the actual cement content and f is the fly ash content. Any type of cement can be used, but the k-value concept is not applied when fly ash is part of the cement. In this latter use, the fly ash is, in effect, taken as having a k-value of 1.0.

K-values can be calculated for many aspects of performance but it is usual to use them for strength. Values of ‘k’ for strength have been reported between 0 and 0.8 (Smith 1967; Wesche et al., 1984 ; Schiessl and Härdtl, 1991; INTRON, 1992; Dhir et al., 2000), depending on fly ash fineness, LOI and content in the mix. Users of the k-value approach usually apply limits on the maximum quantity of fly ash that can be counted as cementitious and restrict the amount by which the cement content can be reduced. A value of k = 0.4 is given in prEN 206-1 (1997) for use with BS EN 450 fly ash up to a maximum accountable fly ash content of 25%, when used in combination with CEM I-42.5 N cement. A value of 0.2 is permitted for use with CEM I-32.5 N cement.

The k-value method is simple to use, but is questionable whether a single k-value of 0.4 can be applicable to the full range of fly ash permitted by BS EN 450. Furthermore, k-values based on strength are not necessarily appropriate to many aspects of durability performance of concrete. Guidance on the methods for measuring the k-value and the problems associated with this method will be given in a CEN report (1998).

Equivalent concrete performance method

The use of equivalent concrete performance method, as originally conceived, permits mix designs that includes non-standard materials, with the aim of producing optimum performance from materials locally available, such as fly ash. The concrete is specified usually by its durability performance and all concretes that meet these requirements irrespective of constituents are considered equivalent. There is no requirement to match the performance of a reference concrete. The limitation of this approach is the lack of standardised durability tests on concrete, and hence any performance tests have to be agreed on a project-by-project basis.

As a way forward, an alternative method of applying the equivalent concrete performance concept for fly ash concrete is given in prEN 206-1 (1997). This method permits amendments to the requirements for minimum cement content and maximum w/c, if a concrete made with a particular fly ash and cement has equivalent performance to a reference concrete meeting the requirements for the relevant exposure condition. The equivalent performance should be judged with respect to the particular specification for which the concrete is intended, especially environmental actions and durability.

The reference concrete against which the fly ash concrete is assessed should contain cement to BS EN 197-1 (1995) and have constituents corresponding to the combination of fly ash and cement.

prEN 206-1 recommends the following limits on the range of fly ash/cement compositions:

(i) the total amount of fly ash should be within the limits in BS EN 197-1 for permitted types of cement

(ii) the sum of cement and fly ash should be at least equal to the minimum cement content in prEN 206-1

(iii) the w/(PC+FA) ratio should be no greater than the maximum w/c in prEN 206-1

Tests (Dhir et al., 1998) have shown that equal performance for chloride ingress, abrasion, freeze-thaw resistance and carbonation can be achieved when the above restrictions are applied and the fly ash concrete has equal 28 day compressive strength to the reference concrete. Therefore for EN 206-1 exposure classes XO, XC, XD and XF no further durability testing is necessary providing that the concrete durability requirements contain a requirement for compressive strength. This makes the equivalent concrete performance method easy to apply as long as the effect of fly ash on strength is known and reliable because the strength is checked.

The fineness of fly ash can affect the performance of concrete and BS EN 450 permits a greater range than BS 3892: Part 1. Because of this, there is a need for a concrete mix design method that can take into account the variations in fineness. Such a mix design method has been developed [6] in which equal strength is achieved for different fly ash concretes by simple adjustment to the free water/(PC+FA) ratio. This may be attained by:

(i) maintaining the existing PC+FA content and adjusting the free water content

(ii) maintaining the existing free water content and adjusting the PC+FA content or

(iii) adjusting both the free water and PC+FA contents.

Treatment with respect to ASR

BRE Digest 330 (1999)recommends that fly ash should conform to BS 3892: Part 1 and it does not cover the wide range of fly ash fineness allowed by BS EN 450. Nevertheless, current European standards and published data do not support this restriction. The fineness limit is, in fact, not required where the FA/PC combination is obtained by inter-grinding providing that all other properties satisfy BS 3892:Part 1.

A definitive guidance is not given on fly ash to BS EN 450 by Digest 330 due to lack of technical data. The use of BS EN 450 FA, hence, should be restricted to concrete not at risk from deterioration due to ASR, either from its intended use or the use of non-reactive aggregates, until data available. However, when checking a concrete for its resistance to ASR, all BS EN 450 FA should be treated as being equally effective as those conforming to BS 3892: Part1. A research programme is in progress at the University of Dundee to confirm this aspect of performance.

MIX DESIGN

A simple approach to applying the equivalent concrete performance method with respect to chloride ingress, abrasion, freeze-thaw resistance and carbonation is the achievement of equal 28-day compressive strength to a suitable reference concrete. Thus, for EN 206-1 exposure classes XO, XC, XD and XF no further durability testing is necessary provided the concrete durability requirements include a minimum cube strength.

Fly ash with properties across the range of BS EN 450 requirements may influence concrete cube strength. A method developed at the University of Dundee (Dhir et al., 1998) takes into account the effects of fly ash characteristics on cube strength by simple adjustment to the free water/(cement + fly ash) ratio, and, therefore, represents a straightforward approach, easy to apply in practice. This method is described below.

The adjustment in the water/(cement + fly ash) ratio to account for variations in fly ash fineness over a range of typical concrete strengths is shown in Figure A-1 for a fly ash content of 30% by mass. The required adjustment in the water/(cement + fly ash) ratio increases with cube strength, because of the increasingly significant effect of fly ash fineness on cube strength as the cement + fly ash content increases.

The following two examples show the selection of water/(cement + fly ash) ratio for two fly ashes, fly ash A with fineness 5% (retained on 45μm sieve) and fly ash B with fineness 35%.

Examples:

Requirement to meet the exposure XC1 for carbonation using 30% fly ash as cement component by mass, (i.e. minimum strength 25 N/mm^2, maximum w/c = 0.65, minimum cement = 260 kg/m^3), where a reference C25 PC concrete with a target strength of 35 N/mm^2 has been shown to perform adequately.

Fly Ash A

Fly ash fineness (% retained 45μm sieve)		5		(1)
Target cube strength of reference concrete		35	N/mm^2	
Figure 2(a). Water/(cement + fly ash) ratio		0.49		(2)
Variation of fineness from 5%	[(1) – 5]/5	0		(3)
Figure 2(b). Correction to Water/(cement + fly ash) ratio				
per 5% fineness variation		5.2×10^{-3}		(4)

Water/(cement + fly ash) ratio (2) – [(3) x (4)]	0.49	

Hence, assuming water content = 165 l/m^3 with a plasticizer in the mix, possible mix proportions are given in Table 5. The aggregate proportions are calculated using normal mix design methods, e.g. BRE Design of normal concrete mixes (BS EN 450, 1995), in which aggregate proportions are calculated by estimating the wet density of concrete, and proportioning the percentage of fine aggregate to the required slump.

Fly Ash B

Fly ash fineness (% retained 45□m sieve)		35	(1)
Target cube strength of reference concrete		35 N/mm^2	
Figure 2(a). Water/(cement + fly ash) ratio		0.49	(2)
Variation of fineness from 5%	[(1) – 5]/5	6	(3)
Figure 2(b). Correction to Water/(cement + fly ash) ratio			
per 5% fineness variation		5.2 x 10^{-3}	(4)
Water/(cement + fly ash) ratio (2) – [(3) x (4)]		0.46	

Corresponding mix proportions for fly ash B would be as given in Table 6. Aggregate proportions have minor adjustments to maintain yield.

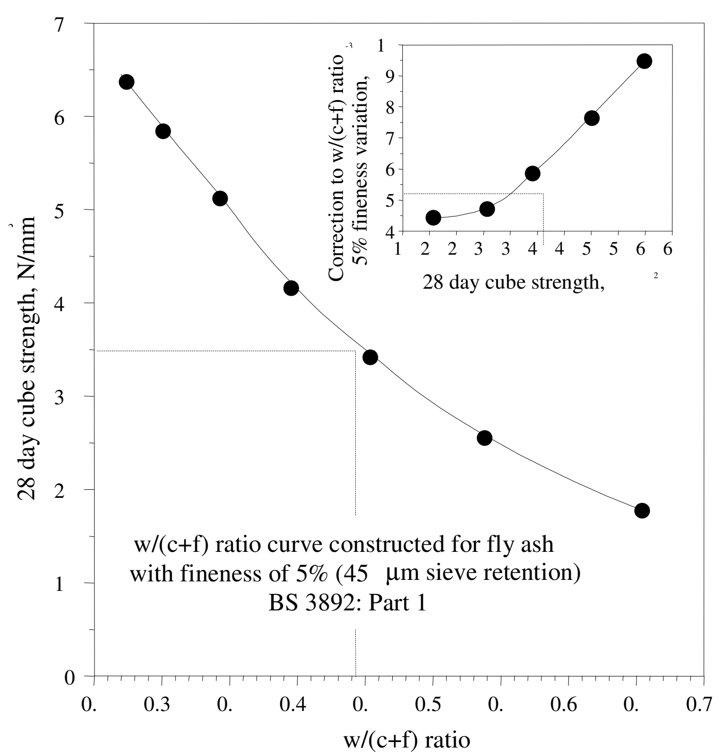

Figure 2 Relationship between water/cement + fly ash ratio (w/(c+f)) and 28 day cube strength for fly ash conforming with BS EN 450. Fly ash content = 30% by mass

Note that the use of the coarser fly ash (B) requires a w/(c+f) ratio 0.03 lower than that for the finer fly ash (A). For the same free water content, this means an increase of 25 kg/m^3 in the total cement + fly ash content. Alternatively, the lower w/(c+f) ratio could have been achieved by reducing the water content, or altering both the water content and cement + fly ash content.

Table 5

Design Strength (N/mm^2)	w/(c+f)	Concrete mix proportions, kg/m^3					
		Free water	PC	Fly ash	Aggregate		
					Fine	10mm	20mm
35.0	0.49	165	235	100	680	405	810

Table 6

Design Strength (N/mm^2)	w/(c+f)	Concrete mix proportions, kg/m^3					
		Free water	PC	Fly ash	Aggregate		
					Fine	10mm	20mm
35.0	0.46	165	250	110	680	395	790

CASE STUDIES

Fly ash to the quality of BS EN 450 has had little use in the UK and most work has involved fly ash to BS 3892: Part 1, with a tightly controlled fineness. Projects that have used coarser fly ash tend to be prior to the introduction of BS 3892: Part 1 in 1982 or projects within the generating industry using "run of station" fly ash.

Ratcliffe cooling tower strengthening

Due to structural problems in some cooling towers at power stations belonging to the CEGB, a programme of strengthening was initiated. This involved adding a mantle of concrete to the outside of the existing shells reported by Woolley and Cabrera (1991). Data is available for the project at Ratcliffe power station (south of Nottingham) for the period from August 1989 to February 1990.

The concrete used had a 28-day characteristic strength of 30 N/mm^2 but to achieve early movement of the formwork, strength of no less than 7 N/mm^2 at 24 hours was required. The mix design had been developed from a plain concrete mix with the fly ash being added as a direct substitution of the cement and represented 35% of the cement + fly ash content. The amount of sand was also slightly reduced to achieve constant yield.

The mean fineness value for the fly ash was 31.0%, varying between 14.4% and 42.9%. This is outside the variability permitted by BS EN 450 (□10%) but is tending towards the finer side.

The mean 28 day cube strength was 49.5 N/mm^2 with a standard deviation of 3.6 N/mm^2. This standard deviation is low despite the fly ash being more variable than permitted by BS EN 450.

The plot of strength results with fly ash fineness in Figure 3 indicates a scatter of results. However, there is a trend towards lower strength in concrete with increasing coarseness of the fly ash. From the diagram it is estimated that the concrete strength at 28 days would be expected to vary by about 4.0 N/mm^2 over a 20% fineness range for the fly ash.

The LOI results recorded over the same period gave a mean of 4.4%, which gives an upper limit based on the statistical factors in BS EN 450 of 6.1%. Two results were above 7.0%, but below 9.0%. This means that the fly ash supplied to the contract would not meet the requirements of BS EN 450 unless, as proposed for the UK, the 7.0% limit was adopted.

The work on the cooling towers demonstrates that good quality concrete can be consistently produced from fly ash that is more variable than required in BS EN 450. This also suggests that the LOI requirements for the UK on a national basis are reasonable.

High Marnham 275 kV substation

High Marnham power station is located close to Newark in Nottinghamshire and was constructed in the period 1956 to 1962; the 275 kV substation associated with the power station was constructed in 1957-58. The concrete for the substation bases were cast in PC concrete, except for a limited number of control areas which contained fly ash. Unusually for the time, the work was well-documented (Howell, 1958) and the concrete was examined 25 years later and the results published (Cabrera and Woolley, 1985).

The materials used were ordinary Portland cement and Trent Valley aggregates, with a maximum size of 38 mm. The fly ash was "run of station" supplied from North Wilford power station in Nottingham. The properties of the cement and fly ash are shown in Table 7.

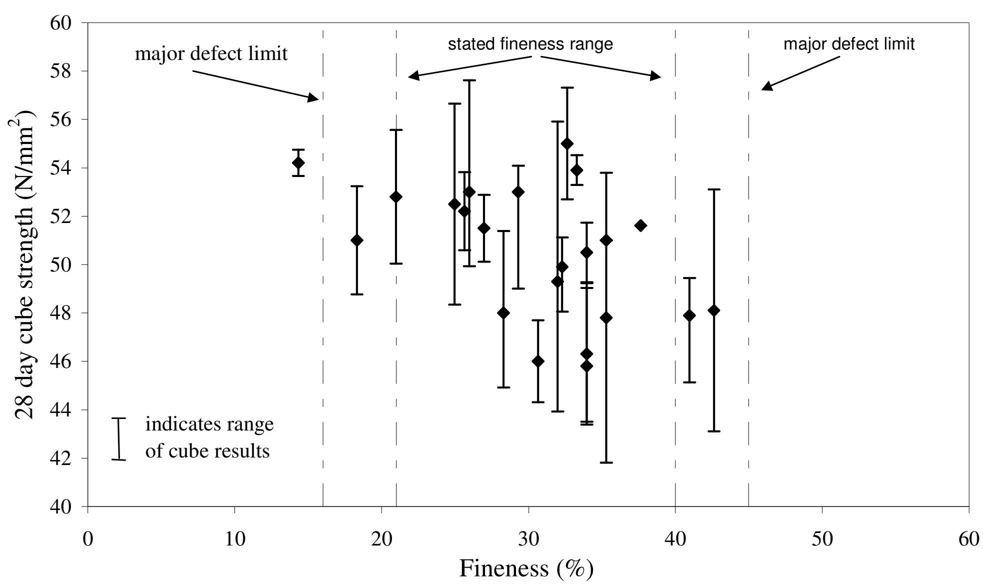

Figure 3 Scatter of strength results with fly ash fineness for Ratcliffe cooling tower strengthening project

The cement was relatively coarse and had a high alkali content. The specific surface at 2250cm^2/g was at the lower limit for Portland cement of the time, and would now be considered as a controlled fineness cement. The alkali content had a total content of 1.22 % sodium equivalent (Na_2O), which would be considered a high alkali cement to BRE Digest 330 (1999).

The fly ash was unusual in its chemistry, the calcium, magnesium and sulfate levels were higher than are typically found, although they are within the limits set in BS EN 450; the alkalis are low (1.26 % sodium equivalent).

The specific surface indicates that the fly ash was finer than the cement, the opposite to what was suggested by the 90µm retention. The fineness of fly ash is currently expressed as 45µm retention, but a mean retention on the 90µm sieve of 12.3% would typically be equivalent to a 45µm retention of around 25%. This is above the limit in BS 3892: Part 1, but within the limits of BS EN 450. There are no data for the variability in fineness of the fly ash, nor any indication of its control.

Table 7 Mean values for OPC and fly ash properties used in High Marnham project

PROPERTY	OPC	FLY ASH
SiO_2 (%)	20.8	46.7
Al_2O_3 (%)	7.2	27.8
Fe_2O_3 (%)	3.3	9.5
CaO (%)	61.7	7.1
MgO (%)	2.3	3.8
Na_2O (%)	0.9	0.9
K_2O (%)	0.5	0.6
SO_3 (%)	1.70	1.24
Loss on Ignition (%)	1.6	2.5
Specific surface [Blaine] (cm^2/g)	2250	3260
“Fineness” (% retained on 90µm)	4.6	12.3
Soundness (mm)	3.1	-
Particle density (g/cm^3)	-	2.03

The details of the mixes are shown in Table 8, with the mix design based on Road Note 4 (Road Research Laboratory, 1950), with a minimum 28-day compressive strength of 21 N/mm^2. Based on the requirements of Road Note 4, the minimum strength should be 60% of the mean, therefore the target mean strength was 35 N/mm^2. The fly ash was added as a direct replacement of cement to represent 20% of the cement + fly ash content by mass. Because the density of fly ash is lower than that of cement, the volume of fines increases. However, there was no correction applied, nor was there any adjustment to the water content, and hence a more workable mix was accepted.

Table 8 Concrete mix design used in High Marnham Project

Material Property	Control mix, kg/m^3	Fly ash mix, kg/m^3
Cement	280	220
Fly ash	-	55
Coarse aggregate	1390	1375
Fine aggregate	600	595
Water	145	145
Water/Cement ratio	0.52	0.52
Nominal slump (mm)	25	40

The results are summarised in Table 9. The compressive strength, expressed as equivalent cube strength, used a factor of 1.15 for all cores, whether they were obtained from horizontal or vertical drilling. This would give conservative results overall.

The strengths of the plain and fly ash concrete are similar after 25 years, although the fly ash concrete had a marginally greater strength gain from one year to 25 years.

Table 9 Summary of strength results from High Marnham project after 25 years (Cabrera and Woolley, 1985)

	Mean equivalent cube compressive strength (N/mm^2)	Indirect tensile Strength (N/mm^2)
Control mix	66.5	4.10
Fly ash mix	69.0	4.20

The plain concrete had slightly higher porosity than the fly ash concrete, the former having a greater quantity of pores of 5μm and above in diameter.

There was no evidence of carbonation of the fly ash concrete, even close to the surface, whereas carbonation was observed up to 15 mm depth in the plain concrete. All bases were set in the ground with upper surfaces exposed to the atmosphere.

Although the alkali content of the concrete was high, no evidence of alkali-silica reaction (ASR) was found (Cabrera and Woolley, 1985).

This case study indicates that even with a simplistic mix design, durable concrete could be made using a relatively coarse fly ash.

AVAILABILITY

The annual production of coal fly ash is around 7 million tonnes, which is produced by a number of coal-fired power stations. The geographical distribution of stations enables fly ash to be supplied to all major cities and industrial centres.

Fly ash is produced twenty-four hours each day, throughout the year, with production varying only with demand for electricity from coal-fired power stations. Most stations have the capability to offer stockpiled conditioned fly ash or lagoon ash to the market alongside dry ash, ensuring adequate availability of supply throughout the annual demand cycle.

For a number of reasons there has been a move away from coal-fired generation of electricity since privatisation of the industry. However, it is now accepted that there is a role for coal as a fuel in electricity generation for the foreseeable future, due to the need to maintain a balanced approach to energy supplies.

There is an increasing emphasis placed by Government and the Market on sustainable developments and waste minimisation. These objectives are met by the utilisation of industrial by-products, like fly ash and reclaimed/recycled materials, which are of particular benefit where there is a proven track record of use in the construction industry.

Further information regarding availability can be obtained from

United Kingdom Quality Ash Association (UKQAA)

Regent House

Bath Avenue

Wolverhampton

West Midlands WV1 4EG

Tel: 01902 576 586

Fax: 01902 576 596

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